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FREE MOLECULE FLOW FORCES AND HEAT TRANSFER FOR AN INFINITE CIRCULAR CYLINDER AT AN ANGLE OF ATTACK

by

L. Talbot

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FLUID FLOW AND
HEAT TRANSFER
AT LOW PRESSURES
AND TEMPERATURES

FREE MOLECULE FLOW FORCES AND HEAT TRANSFER FOR AN INFINITE CIRCULAR CYLINDER AT AN ANGLE OF ATTACK

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L. Talbot

FACULTY INVESTIGATORS:

S. A. Schaaf, Associate Professor of Engineering Science

L. Talbot, Assistant Professor of Mechanical Engineering

Approved by: S A Schaaf

ABSTRACT:

Expressions are derived for the recovery factor and heat transfer and the normal and tangential force characteristics of an infinite circular cylinder at arbitrary angle of attack in free molecule flow. The results are expressed in closed form for a cylinder at arbitrary uniform temperature in terms of three gross molecular surface interaction coefficients, the normal and tengential momentum transfer coefficients and the thermal accommodation coefficient.

Free Molecule Flow Forces and Heat Transfer for an Infinite Circular Cylinder at an Angle of Attack

The calculations of Stalder, et al. (Refs. 1 and 2) for the force and heat transfer characteristics of an infinite cylinder transverse to a free molecule flow can be extended to include the case of arbitrary angle of attack at zero yaw.

I Heat Transfer to a Surface Element

Assuming that the undisturbed flow is in Maxwellian equilibrium, the distribution function for the incident molecules is given by

$$f = \frac{\rho}{m}(2\pi RT)^{-3/2} \exp\left\{-\frac{(u - U\sin\theta)^2 + (v + U\cos\theta)^2 + w^2}{2RT}\right\} \qquad (1)$$

where u, v, w are molecular velocities in the x, y, z directions of Fig. 1, U is the gas velocity, ρ the gas density ($p = \rho RT$), m the mass of a molecule, and θ the local angle of attack of the surface element. The flux of energy incident on the surface element dA is comprised of translational molecular energy, $dE_{i,trans}$, and internal energy, $dE_{i,int}$. The first is given by

$$dE_{i,trans} = dA\int_{-\infty}^{\infty} dw \int_{-\infty}^{\infty} dv \int_{0}^{\infty} \frac{1}{2} m(u^2 + v^2 + w^2)\, u f \, du$$

$$= \rho RT\sqrt{\frac{RT}{2\pi}}\, dA\left\{\left(s^2 + \frac{1}{2}\right)e^{-(s\sin\theta)^2} + \sqrt{\pi}\left(s^2 + \frac{5}{2}\right)(s\sin\theta)\left[1 + \operatorname{erf}(s\sin\theta)\right]\right\} \qquad (2)$$

where $s = U/\sqrt{2RT}$ is the molecular speed ratio and erf(x) is the error function $2/\sqrt{\pi}\int_0^x e^{-t^2}dt$. The number of molecules striking dA per unit time is

$$dN_i = dA\int_{-\infty}^{\infty}dw\int_{-\infty}^{\infty}dv\int_0^{\infty}u f du$$

$$= \frac{\rho}{m}\sqrt{\frac{RT}{2\pi}}\left\{e^{-(s\sin\theta)^2}+\sqrt{\pi}(s\sin\theta)\left[1+\operatorname{erf}(s\sin\theta)\right]\right\}dA \qquad (3)$$

According to the principle of equipartition of energy, each molecule carries, on the average, $\frac{jRT}{2}$ units of internal energy per unit mass, where j is the equivalent number of fully excited internal degrees of freedom of the molecule. In terms of the specific heat ratio γ , $j = \frac{5-3\gamma}{\gamma-1}$. Then the flux of internal energy to dA is

$$dE_{i,int} = \frac{5-3\gamma}{2(\gamma-1)}\, mRT\, dN_i$$

$$= \frac{5-3\gamma}{(\gamma-1)\sqrt{\pi}}\left(\frac{RT}{2}\right)^{1/2}\left\{e^{-(s\sin\theta)^2}+\sqrt{\pi}(s\sin\theta)\left[1+\operatorname{erf}(s\sin\theta)\right]\right\}dA \qquad (4)$$

We now define a thermal accommodation coefficient α for the surface interaction

$$\alpha = \frac{dE_i - dE_r}{dE_i - dE_w} \qquad (5)$$

where $dE_i = dE_{i,trans} + dE_{i,int}$; dE_r is the total energy flux of the molecules re-emitted from the surface; and dE_w the energy flux which would be re-emitted if all molecules left in Maxwellian equilibrium at the surface temperature T_w. It is easily shown that

$$dE_w = (4+j)\frac{mRT_w}{2}\,dN_w = (4+j)\frac{mRT_w}{2}\,dN_i \tag{6}$$

The total convective heat transfer to the surface dA is

$$dQ = dE_i - dE_r = \left(dE_{i,\,trans} + dE_{i,\,int}\right)\alpha - \alpha\, dE_w \tag{7}$$

Then, in terms of the appropriate integrals

$$dQ = \alpha\rho RT\sqrt{\frac{RT}{2\pi}}\left\{\left(s^2+\frac{\gamma}{\gamma-1} - \frac{\gamma+1}{2(\gamma-1)}\frac{T_w}{T}\right)\left(e^{-(s\sin\theta)^2} + \sqrt{\pi}(s\sin\theta)\left[1+\operatorname{erf}(s\sin\theta)\right]\right) - \frac{1}{2}e^{-(s\sin\theta)^2}\right\}dA \tag{8}$$

II Stresses on a Surface Element

The stress calculations require the introduction of two additional surface interaction parameters

$$\sigma = \frac{\tau_i - \tau_r}{\tau_i} \tag{9}$$

$$\sigma' = \frac{p_i - p_r}{p_i - p_w} \tag{10}$$

where τ_i and τ_r are the incident and re-emitted tangential momentum fluxes, and p_i, p_r, p_w are respectively the normal fluxes of momentum incident, re-emitted, and that which would be re-emitted if all molecules left in Maxwellian equilibrium with the surface. We have then,

$$p_i = \int_{-\infty}^{\infty} dw \int_{-\infty}^{\infty} dv \int_{0}^{\infty} m u^2 f \, du$$

$$= \frac{\rho U^2}{2\sqrt{\pi}\, s} \left\{ (s \sin\theta) e^{-(s\sin\theta)^2} + \sqrt{\pi}\left[\frac{1}{2} + (s\sin\theta)^2\right]\left[1 + \operatorname{erf}(s\sin\theta)\right] \right\} \tag{11}$$

$$\tau_i = \int_{-\infty}^{\infty} dw \int_{-\infty}^{\infty} dv \int_{0}^{\infty} m u v f \, du$$

$$= -\frac{\rho U^2 \cos\theta}{2\sqrt{\pi}\, s} \left\{ e^{-(s\sin\theta)^2} + \sqrt{\pi}(s\sin\theta)\left[1 + \operatorname{erf}(s\sin\theta)\right] \right\} \tag{12}$$

(The minus sign indicates that τ_i acts in the direction of negative y in Fig. 1)

The net normal and shear stresses on dA are

$$p = p_i + p_r = (2 - \sigma')p_i + \sigma' p_w \tag{13}$$

$$\tau = \tau_i - \tau_r = \sigma \tau_i \tag{14}$$

and, with

$$p_w = \frac{1}{2} m \sqrt{2\pi R T_w} \frac{dN_i}{dA} \tag{15}$$

(see Refs. 3, 4), the final expressions are

$$p = \frac{\rho U^2}{2 s^2} \left\{ \left(\frac{2-\sigma'}{\sqrt{\pi}} s\sin\theta + \frac{\sigma'}{2}\sqrt{\frac{T_w}{T}} \right) e^{-(s\sin\theta)^2} + \left[(2-\sigma')\left(s^2\sin^2\theta + \frac{1}{2}\right) + \frac{\sigma'}{2}\sqrt{\frac{\pi T_w}{T}}(s\sin\theta) \right]\left[1 + \operatorname{erf}(s\sin\theta)\right] \right\} \tag{16}$$

$$\tau = -\frac{\sigma \rho U^2 \cos\theta}{2\sqrt{\pi}\, s^2} \left\{ e^{-(s\sin\theta)^2} + \sqrt{\pi}(s\sin\theta)\left[1 + \operatorname{erf}(s\sin\theta)\right] \right\} \tag{17}$$

The expressions, Eqs. 8 and 17, are identical with those obtained in Refs. 1, 2, except that they are presented in the more convenient form first used by Schaaf and Chambré (Ref. 3). Eq. 16 differs from the equivalent result of Ref. 1 in that the additional surface interaction parameter σ' (Ref. 4) is included.

III Integration of the Stress and Heat Flux Equations Over the Cylinder

The coordinate system on the cylinder and the appropriate angles are shown in Fig. 2. The angle of attack is β. It is assumed that the parameters σ, σ', and α, and the surface temperature T_w are constant over the entire cylindrical surface.

For the heat transfer per unit length of cylinder, with d the cylinder diameter, we have

$$\frac{Q}{\alpha \rho d R T \sqrt{\frac{RT}{2\pi}}} = \int_{-\pi/2}^{\pi/2} \left\{ \left(s^2 + \frac{\gamma}{\gamma-1} - \frac{\gamma+1}{2(\gamma-1)} \frac{T_w}{T} \right) \left(e^{-(\xi \sin\phi)^2} + \sqrt{\pi}\, \xi \sin\phi \left[1 + \operatorname{erf}(\xi \sin\phi) \right] \right) - \frac{1}{2} e^{-(\xi \sin\phi)^2} \right\} d\phi \tag{18}$$

in which $\xi = s \sin\beta$. The results of the integrations may be conveniently expressed in terms of a Stanton number St and recovery factor r defined by

$$St = \frac{Q}{\pi d \rho U C_p (T_{aw} - T_w)} \tag{19}$$

$$r = \frac{T_{AW} - T}{T_0 - T} \tag{20}$$

where C_p is the constant pressure specific heat of the gas, T_{aw} is the adiabatic cylinder temperature ($Q = 0$), and T_0 the adiabatic stagnation temperature of the gas. We find that

$$St = \frac{\alpha(\gamma+1)}{4\gamma\sqrt{\pi}\, s}\, e^{-\xi^2/2} \left\{ (1+\xi^2) I_0\left(\frac{\xi^2}{2}\right) + \xi^2 I_1\left(\frac{\xi^2}{2}\right) \right\} \tag{21}$$

$$r = \frac{\gamma}{(\gamma+1)\, s^2}\; \frac{\left[\xi^2 + 2s^2(1+\xi^2)\right] I_0\left(\frac{\xi^2}{2}\right) + \left[2s^2\xi^2 + \xi^2\right] I_1\left(\frac{\xi^2}{2}\right)}{(1+\xi^2) I_0\left(\frac{\xi^2}{2}\right) + \xi^2 I_1\left(\frac{\xi^2}{2}\right)} \tag{22}$$

where $I_0\left(\frac{\xi^2}{2}\right)$ and $I_1\left(\frac{\xi^2}{2}\right)$ are modified Bessel functions of the first kind.

The force calculations are most conveniently expressed in terms of the normal and tangential coefficients

$$C_N = \frac{N}{\frac{1}{2}\rho U^2 d} \tag{23}$$

$$C_T = \frac{T}{\frac{1}{2}\rho U^2 d} \tag{24}$$

where N and T are the forces per unit length of cylinder normal to and parallel to the cylinder axis. We have

$$\begin{aligned} C_N = \int_{-\pi/2}^{\pi/2} \Bigg\{ & e^{-(\xi \sin\phi)^2} \left[\frac{\sigma \sin\beta \cos^2\phi}{s\sqrt{\pi}} + \frac{2-\sigma'}{\sqrt{\pi}} \xi \sin^2\phi + \frac{\sigma'}{2}\sqrt{\frac{T_w}{T}} \sin\phi \right] \\ & + \operatorname{erf}(\xi \sin\phi) \Big[(2-\sigma')\left(\xi^2 \sin^3\phi + \tfrac{1}{2}\sin\phi\right) + \frac{\sigma'}{2}\xi\sqrt{\frac{\pi T_w}{T}} \sin^2\phi \\ & \qquad + \sqrt{\pi}\, \xi \cos^2\phi \sin\phi \Big] \\ & + \frac{\xi \sigma \sin\beta}{s} \cos^2\phi \sin\phi + \frac{2-\sigma'}{\sqrt{\pi}}\left(\xi^2 \sin^3\phi + \tfrac{1}{2}\sin\phi\right) \\ & + \frac{\xi\sigma'}{2}\sqrt{\frac{\pi T_w}{T}} \sin^2\phi \Bigg\} d\phi \end{aligned} \tag{25}$$

and

$$C_T = \frac{\sigma \cos\beta}{\sqrt{\pi}\, S} \int_{-\pi/2}^{\pi/2} \left\{ e^{-(\xi \sin\phi)^2} + \sqrt{\pi}\, \xi \sin\phi \left[1 + \operatorname{erf}(\xi \sin\phi) \right] \right\} d\phi \tag{26}$$

These integrals, when evaluated, give

$$C_N = \frac{\sqrt{\pi} \sin\beta \,(4+\sigma-2\sigma')}{S} e^{-\xi^2/2} \left[\left(\tfrac{1}{2}+\tfrac{1}{3}\xi^2\right) I_0\!\left(\tfrac{\xi^2}{2}\right) + \left(\tfrac{1}{6}+\tfrac{1}{3}\xi^2\right) I_1\!\left(\tfrac{\xi^2}{2}\right) \right] + \frac{\sigma' \sin\beta\, \pi^{3/2} \sqrt{2RT_w}}{4U} \tag{27}$$

$$C_T = \frac{\sigma \cos\beta \sqrt{\pi}}{S} e^{-\xi^2/2} \left[(1+\xi^2) I_0\!\left(\tfrac{\xi^2}{2}\right) + \xi^2 I_1\!\left(\tfrac{\xi^2}{2}\right) \right] \tag{28}$$

The final results, Eqs. 21, 22, 27, 28, agree with those obtained in refs. 1 and 2 for $\beta = 90^\circ$, and for $\beta = 0$, for the two particular cases of molecule-surface interaction that the authors have considered, namely, perfectly diffuse reflection $(\sigma = \sigma' = \alpha = 1)$ and perfectly specular reflection $(\sigma = \sigma' = \alpha = 0)$.

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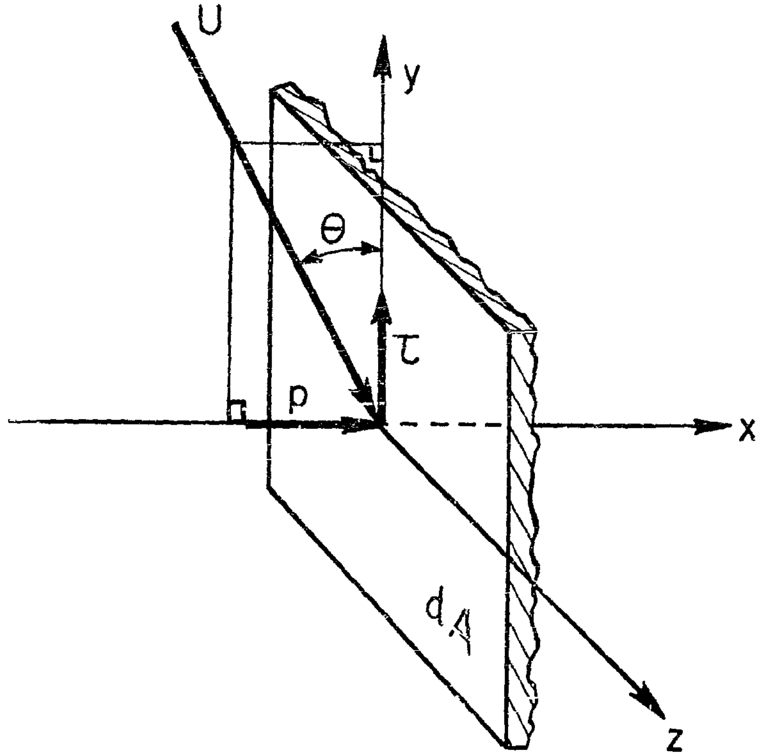

FIG. I LOCAL COORDINATE SYSTEM

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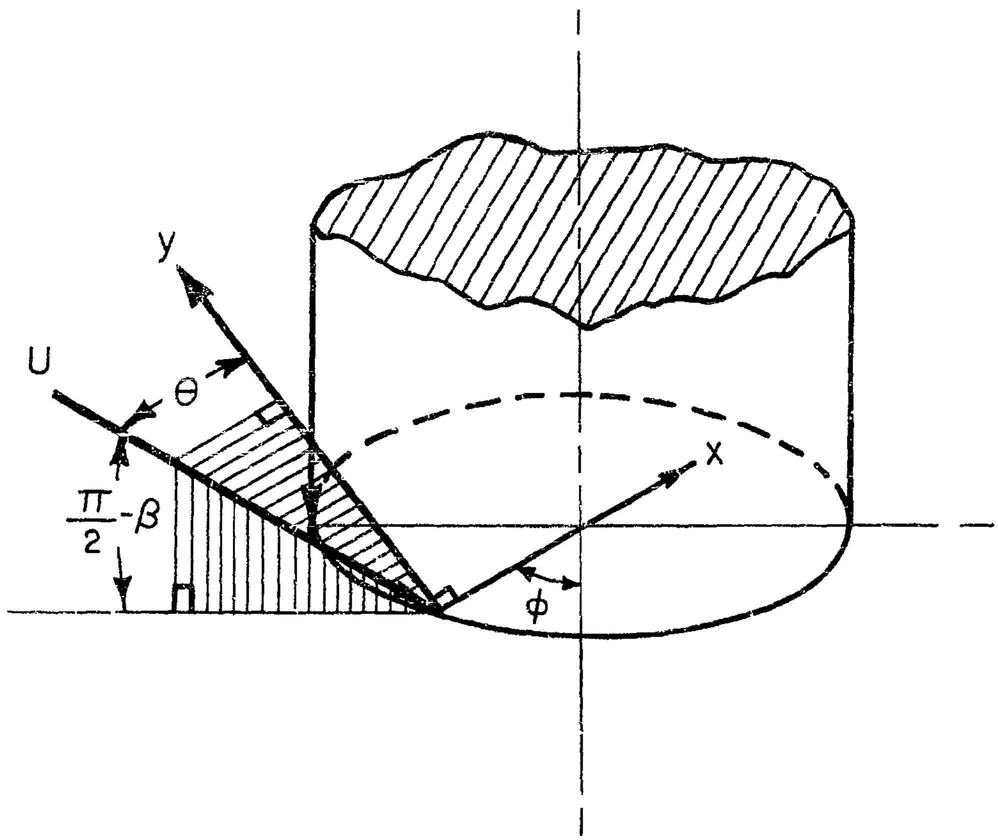

FIG. 2 COORDINATE SYSTEM ON SURFACE OF CYLINDER

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University of Michigan
Ann Arbor, Michigan (1)

J. R. Stalder
1831 Hamilton Avenue
Palo Alto, California (1)

Professor Paul A. Libby
Dept. of Aero. Engineering
Polytechnic Institute of Brooklyn
99 Livingston Street
Brooklyn, New York (1)

Professor K. Stewartsen
Department of Mathematics
Bristol University
Bristol, England (1)

Professor Harold Grad
Institute for Math and Mech.
New York University
45 Fourth Avenue
New York 3, New York

Dr. R. J. Emrich
Department of Physics
Lehigh University
Bethlehem, Pennsylvania (1)

Dr. J. O. Herschfelder
P. O. Box 2127
Madison 6, Wisconsin (1)

Commander
Western Development Division
Post Office Box 262
Inglewood, California (1)